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Strength Prediction Model for Concrete

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***Abstract*—There are many parameters of concrete that influence its strength gaining characteristics. This study is an attempt to use the early compressive strength test result to estimate compressive strength at different ages. Potential utilization of the early day compressive strength result to predict characteristic strength of normal weight concrete has been investigated. A simple mathematical model capable of predicting the compressive strength of concrete at any age is proposed for both stone and local aggregate concrete. The basic model consists of a rational polynomial equation having only two coefficients. This study also proposes a simple reliable relationship between the coefficient p (strength at infinite time) with the strength values of concrete of a particular day. This relation greatly simplifies the concrete strength prediction model. The developed model is validated for commonly used stone aggregate concrete and also for local (brick) aggregate concrete. Data used in this study are collected from some previous studies and recent experimental works. The analysis carried with the model using different data exhibit reliable prediction of concrete strength at different ages (7, 14, 28 days etc.) with excellent efficiency.**

***Index Terms*—concrete strength, local aggregate concrete, stone aggregate concrete, strength prediction.**

I. Introduction

Compressive strength of concrete has been considered as an index of quality control for many years. Quality of the concrete is generally determined by the compressive strength test of the concrete cylinder. When engineers design a concrete structure they basically rely on the characteristic strength of the concrete. Characteristic strength of the concrete is usually designated as the strength of concrete sample that has been cured for 28 days. This is generally determined by the standard cylinder crushing tests of concrete. Most of the code for concrete design also recommends 28 days strength to consider in design. In construction works 28 days is a considerable time to wait, while it is essential for quality assurance of concrete and cannot be avoided. So waiting at least 28 days is mandatory for the confirmation of the quality and the desired strength. An easy and reliable method for estimating the final strength at an early age (as early as possible) of concrete may enable one to know the quality of the concrete and its probable weakness. It may help to decide whether to continue the construction or manage the destruction of the bad concrete. An early decision in this respect is a long felt matter [1].

Theoretically in order to model a system it is required to understand the explicit mathematical input and output relationship precisely. Such explicit mathematical modeling is difficult and is not readily tractable in poorly understood system. Most of the proposed prediction model is based on the relationship between the concrete strength and its constituent characteristics [2]. Different researchers tried to make choice of different variables taking into account different characteristics and proportioning of the concrete ingredients which influences the behavior of the concrete.

This paper is an attempt to use only the early strength test result to predict the concrete strength at different ages instead of taking other factors into consideration. A relationship of concrete strength with the age of concrete is discussed and finally expressed with a simple mathematical model. The model is established from studying the crushing strength test results of cylinders of normal weight concrete [3] and further validated with test results done in different countries [4,5]. All the predicted results yield very good correlation with the actual.

II. Previous Studies

Strength gaining process of concrete is a multi-factor dependent complex process. There are numerous studies in this regard. Even at present the researchers have shown keen interest in it. Knowing concrete strength gain pattern enables to predict the concrete characteristic strength at an early age and gives an idea about the quality of the concrete compliance with the design requirement.

Several improved techniques including empirical/computational modeling with Artificial Neural Network, Genetic Algorithm, Fuzzy Logic [6-8] etc. and statistical technique have been introduced to solve the problem of strength prediction at different ages. A number of research efforts have concentrated on using linear regression model to improve the accuracy of prediction. Most popular linear regression equation (Eq. 1) which is often used in strength prediction, relates water-cement ratio (w/c) to strength of concrete.

$$f = b_0 + b_1 \, . \, w/c \qquad (1)$$

Where f = compressive strength of concrete; b_0, b1 are coefficients. The origin of the above equation is Abram's

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Law [9] which inspires to develop multivariable linear regression equation as follows:

$$f = b_0 + b_1X_1 + b_2X_2 + b_3X_3 \dots\dots + b_nX_n \quad (2)$$

Where, X_1, X_2, X_3,……,X_n are variable which can be replaced by the factors that influences the concrete behavior like water-cement ratio (w/c), quantity of cement (C), quantity of coarse aggregate (CA) quantity of fine aggregate (FA) etc. in the concrete mix.

In a recent study [5], multivariable power equation was chosen as an effective model for prediction of strength of different ages of concrete. The general format of the equation is given below (Eq.3):

$$Y = a_0X_1^{a_1}X_2^{a_2}X_3^{a_3} \dots\dots\dots X_m^{a_n} \quad (3)$$

In the above equation compressive strength of a particular day (Y or f_{age}) is considered as the dependent variable on the variables which has significant correlation with the strength like the water-cement ratio (w/c), cement (C), water (W), sand (FA), aggregate (CA) content, density of concrete (ρ) and the above Equation becomes:

$$f_{age} = a_0C^{a_1}W^{a_2}FA^{a_3}CA^{a_4}\rho^{a_5}(w/c)^{a_6} \quad (4)$$

The values of a_0, a_1, a_2, a_3, a_4, a_5 and a_6 are determined from regression analysis of the statistical data and it is possible to predict the strength of concrete for a particular age directly.

Most of the models discussed above consider different index properties of concrete which influence the strength gaining behavior. This study is an exception because it shows the importance of using only the strength test result of a particular day as an alternative of using the other index parameters.

III. Data Acquisation

Modeling a problem is basically nothing but to find out the relations between different parameters. For this reason, a very large number of experimental results or practical case study is required to determine and justify the interactions among various characteristics. Data used in the current program are collected from the literature and fresh experimental works done in the laboratory. Different data sources increase the versatility of the work and strengthen validity of the formulation.

Total four groups of data from different sources are used in this program. Among them two are collected from the previous work and rest two are collected from recent experimental works undertaken in the laboratories of Bangladesh University of Engineering and Technology (BUET) and Dhaka University of Engineering and Technology (DUET), Bangladesh. Different sources of data are classified into groups for ease of presentation. The data groups are named as Group 1 through Group 4. Total 56 sets of data are available in Group 1 which is imported from a previous study by Garg [3]. This Group data are basically used for analyzing the concrete strength gaining behavior and development of the initial model. The 2nd group of data (Group 2) is collected from the experiments done in the Concrete Laboratory of BUET by Hasan[2]. This Group 2 data are used for the validation of the primary model. Total 23 sets of data are available in this Group.

To authenticate the developed model and also for the extension of the proposed idea, two more groups of data are used. The Group-3 data is collected from a previously published work of Zain et al [5] containing 18 sets of data. Three of the four groups (Group-1 to Group-3) of data summarized in Table I are for stone aggregate normal strength concrete made with ordinary Portland cement (OPC) and with no admixture or additives.

The last group (Group-4) included are test results of concrete made with local aggregates (brick chips). These are relatively light weight coarse aggregates (crushed brick chips) widely used in concrete construction in Bangladesh. The last column of the Table I, shows the summary of these brick aggregate (Group-4) concrete property data. Only the general constituents of concrete [Cement(C), Coarse-Aggregate (CA),

Table I. Property Ranges Of Group 1 - Group 4 Test Data

Name	Unit	Range (Group-1)	Range (Group-2)	Range (Group-3)	Range (Group-4)
Coarse aggregate (CA)	(kg/m^3)	985-1078	1042-1124	914-1300	735-770
Fine aggregate (FA)	(kg/m^3)	665-826	630-826	457-650	610-640
Cement (C)	(kg/m^3)	356-475	312-448	305-517	300-375
Water (W)	(kg/m^3)	185,190	177-255	147-320	135-205
Fineness modulus (FM) of fine aggregate		2.4, 2.6	2.56	2.82	2.43
W/C ratio		0.40-0.52	0.40-0.76	0.45-0.70	0.45-0.55
CA type	(mm)	Stone	Stone	Stone	Local Brick
3 day test strength	MPa	-	5.29-23.61	12.3-26.1	-
7 day test strength	MPa	13.84-27.82	8.61-31.86	14.6-44	8.87-20.35
14 day test strength	MPa	17.8-37.6	-	-	12.38-23.5
28 day test strength	MPa	19.53-39.37	12.37-39.06	23.8-44	13.97-29.99

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Fine-Aggregate (FA) and Water (W)] are considered to influence the concrete compressive strength. Different mix proportions of the ingredients and different w/c ratio are used to study the variations.

IV. Mathematical Model

Clear understanding of the unambiguous input output relationship is a prerequisite to express a function theoretically in the form of a mathematical model. It is quite impossible to model a system without precise knowledge over the behavior of the system. That's why adequate number of practical and experimental results is necessary in order to explore the behavior of the system. This study is concentrated to make the concrete strength predictable from result of an early day's test. As several days of test results are available for the Group 1 data, these are carefully used to establish the concrete strength gaining nature with ages [10].

A. The Initial Model

Strength versus age (day) curve is plotted for every single data set of Group 1. Investigation shows that all the concrete strength maintains a correlation with its age according to the following simple equation:

$$f'_{c,D} = \frac{D}{D+q}\, p \tag{5}$$

Where, $f'_{c,D}$= Strength of the concrete at D^{th} day (D = number of days i.e., 1, 2, 3...7…etc.); p and q are constants for each curve but different for different data set (curve). This fundamental relationship is developed based on Group-1 data. It may be mentioned that this equation (Eq. 5) is similar to the equation (Eq. 6) proposed by ACI committee (ACI 209-71) [12] for predicting compressive strength of concrete at any day based on 28 days strength.

$$(f_c{}')_t = \frac{t}{a+b.t}.(f'_c)_{28d} \tag{6}$$

Here, a and b are constants and $(f'_c)_{28d}$= 28-day cylinder crushing strength and t is the time in days.

However, for this study Eq. 5 is the basic equation to express the strength of concrete as a function of its age where p and q are two constants. It is observed that the strength gaining pattern is regulated by the values of the two constants p and q. To utilize the derived equation (Eq. 5), the values of these two constants (p and q) are to be determined for each individual case. It may be mentioned that the constant q has the unit of day and p has the unit of stress to be consistent with the expression.

Simplest way to determine the values of p and q is to use the strength test result of two different days and thus solve the simultaneous equations. However, a different approach is possible using a particular day's compressive strength test result to find the values of p and q [10]. From regression analysis, it is observed that values of p can be expressed as a function of q and $f'_{c,D}$ which is a polynomial surface equation [2, 11]. Thus,

$$p = a + b.q + c.f'_{c,D} + d.q.f'_{c,D} + e.\{f'_{c,D}\}^2 \tag{7}$$

Where, $f'_{c,D}$= Strength of concrete at D^{th} day and a, b, c, d and e are the coefficients. The values of these five coefficients will differ for the strength test result of different days [10, 11] and may be obtained from regression analysis of sufficient available data for strength values of a particular day's test. Now, if the strength of a particular day (7^{th} or 14^{th} day) is known then Eqs. 7 and 5 along with the determined coefficients (a, b, c, d, and e), can be used to compute the values of p and q for that particular concrete. Eventually, this can be used to evaluate concrete strength at different ages from Eq. 5.

A. Revised Model

Though the above model (Eq. 5 & 7) has the potential to predict concrete strength for different days, it has 5 coefficients of its own (Eq. 7) which need to be determined for a particular type of concrete. Also, so many constants are difficult to handle on regular basis. Reducing the constants can increase the adaptability of the proposed model. So, the available results are further analyzed and it is observed that the value of p can be more simply related with concrete strength using a power equation. This can be expressed as stated below (Eq. 8). It simplifies the problem of prediction significantly.

$$p = m(f'_{c,D})^r \tag{8}$$

Where, $f'_{c,D}$= Strength of the concrete at D^{th} day and m and r are the coefficients.

Studying the available Group-1 and Group-2 test data, these coefficients (m and r) are determined from best fit equation. It has been found that the value of r remains unchanged but the m value differs for strength test results of different days. With slight rounding the value of r is taken as 0.80; this and the values of m for different day's strength results are given in the Table II along with the corresponding equation that result.

Plots of Eq. 8 for different days of strength results are shown in Fig. 1. The values of m are taken from Table II and r = 0.80 for every case. Thus, the corresponding p values can be obtained by putting known 3 days, 7 days or 14 days concrete strength values in Eq. 8 in appropriate form as given in Table II or Fig. 1. Then, q is computed from Eq. 5 using 3, 7 or 14 days strength value and the p-value obtained in the last step. Finally, the determined q and p-value may be used to find the strength of concrete at any days.

V. Performance Evaluation

The acceptance of any model is basically dependent on its performance. There are different procedures of measuring that. Use of statistical parameters is a popular method of performance analysis, which is some system of comparison

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TABLE II. VALUES OF COEFFICIENTS *m* FOR DIFFERENT DAY'S STRENGTH

Concrete age, D (day)	Value of m	Value of r	Formulated Equation
3	3.8	0.80	$p = 3.8(f'_{c,3})^{0.80}$
7	3.0	0.80	$p = 3.0(f'_{c,7})^{0.80}$
14	2.5	0.80	$p = 2.5(f'_{c,14})^{0.80}$

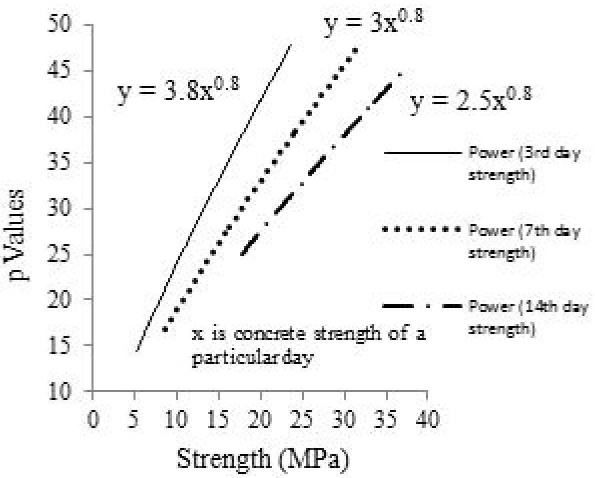

Figure 1.Variation of p with the strength of the concrete

of output results obtained from the model with actual field or laboratory results. The performance of the proposed equations are evaluated by three popular statistical parameters like, mean absolute error (MAE), root mean square error (RMSE) and normal efficiency (EF); their expressions are given below.

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|P_i - A_i| \tag{9}$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - A_i)^2} \tag{10}$$

$$\text{EF} = \left(1 - \frac{1}{n}\sum_{i=1}^{n}\frac{|Pi - A_i|}{A_i}\right) \times 100\ \% \tag{11}$$

Here, Ai = Actual value; Pi = Predicted value; n = number of data (1, 2, 3 …).

In total 124 data sets are used in this study. Among them 79 sets of data are used for modeling the problem and rest are used for performance evaluation. Group 1 and 2 data are primarily used for development of the model and others are used for the performance test.

A. Test with Stone Aggregate

Group 1 to Group 3 data are all concrete cylinder strength test results of stone aggregate concrete made with ordinary Portland cement. Group 1 and 2 results are utilised to develop both the initial and revised models for predicting concrete strength from single day's test. The prediction capability of these models for all the available data sets of these two groups has been compared in two previous works [10, 11]. Here, only the performance summary of prediction using revised model is listed in the Table III. For Group 1, prediction of 14 and 28 days strength is compared based on 7 days result and again prediction of 7 and 28 days stregnth are compared based on 14 days result. The comparison basis for Group 2 data are 3 and 7 days instead of 7 and 14.

TABLE III. PERFORMANCE SUMMARY FOR GROUP-1 & GROUP-2 DATA

Data Group-1				
Base Strength ($f'_{c,D}$)	$f'_{c,7}$ (D=7)		$f'_{c,14}$ (D=14)	
Predicted Strength ($f'_{c,D}$)	$f'_{c,14}$ (D=14)	$f'_{c,28}$ (D=28)	$f'_{c,7}$ (D=7)	$f'_{c,28}$ (D=28)
RMSE	2.33	2.79	2.15	2.70
MAE	1.90	2.42	1.72	2.21
EF (%)	92.8	91.6	91.9	92.4
Avg. Pi/Ai	1.00	0.99	1.01	0.99
Min Pi/Ai	0.83	0.80	0.80	0.80
Max Pi/Ai	1.22	1.22	1.20	1.20
Data Group-2				
Base Strength ($f'_{c,D}$)	$f'_{c,3}$ (D=3)		$f'_{c,7}$ (D=7)	
Predicted Strength ($f'_{c,D}$)	$f'_{c,7}$ (D=7)	$f'_{c,28}$ (D=28)	$f'_{c,3}$ (D=3)	$f'_{c,28}$ (D=28)
RMSE	2.00	2.52	1.51	2.18
MAE	2.00	2.00	1.00	2.00
EF (%)	91.20	91.9	90.2	92.0
Avg. Pi/Ai	0.98	0.97	0.99	1.04
Min Pi/Ai	0.80	0.84	0.79	0.81
Max Pi/Ai	1.20	1.15	1.23	1.15

Group-3 data are taken from works of Zain et al. [5] in oder to validate the above model and check its efficiency. These data are chosen because they belong to same category of concrete (stone aggregate normal weight concrete) as that of the model. However these test were carried in a different country with different source of aggregates. One to one prediction results of this group is given in Table IV and overall performance effectiveness is summarised in Table V.

B. Test with Local Aggregate

In Bangladesh brick chips are very popular locally used concrete ingredients for construction purpose. Concrete made with brick chips are called local aggregate concrete. This type of concrete has the same pattern of strength gaining charecteristics when made with OPC. It is presumed that the developed model should be equally effective for this local aggregate concrete. To check this criteria the developed model is further used to evalute the concrete strength of

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TABLE IV. PREDICTED STRENGTH USING PROPOSED MODEL FOR GROUP-3 DATA

Mix no.	Actual Strength, A_i ($f'_{c,D}$)			Predicted Strength, P_i ($f'_{c,D}$)			
				Using $f'_{c,3}$ value		Using $f'_{c,7}$ value	
	$f'_{c,3}$	$f'_{c,7}$	$f'_{c,28}$	$f'_{c,7}$	$f'_{c,28}$	$f'_{c,3}$	$f'_{c,28}$
1	17.9	24.5	34.0	25.71	34.06	16.44	33.84
2	17.4	22.5	32.5	25.04	33.26	14.95	31.43
3	16.3	21.6	32.5	23.58	31.48	14.29	30.33
4	16.1	21.5	32.3	23.31	31.16	14.22	30.21
5	15.0	21.1	30.5	21.83	29.35	13.92	29.72
6	14.6	20.4	30.3	21.29	28.69	13.41	28.86
7	14.1	20.3	29.2	20.62	27.86	13.34	28.73
8	14.1	20.0	28.9	20.62	27.86	13.12	28.36
9	13.9	18.5	27.7	20.35	27.53	12.04	26.50
10	13.7	17.6	25.9	20.08	27.20	11.39	25.37
11	13.2	17.3	24.5	19.40	26.36	11.18	25.00
12	12.3	14.6	23.8	18.17	24.83	9.28	21.55
13	26.1	31.0	44.0	36.39	46.75	21.38	41.51
14	23.0	29.9	39.4	32.39	42.05	20.53	40.23
15	21.4	28.3	37.5	30.31	39.58	19.30	38.35
16	19.6	26.7	36.1	27.95	36.76	18.09	36.46
17	19.5	25.8	35.2	27.82	36.60	17.41	35.39
18	18.4	25.7	34.6	26.37	34.86	17.33	35.28

TABLE V. PERFORMANCE SUMMARY FOR GROUP-3 DATA

Data	Group-3			
Used Strength ($f'_{c,D}$)	$f'_{c,3}$ (D=3)		$f'_{c,7}$ (D=7)	
Predicted Strength ($f'_{c,D}$)	$f'_{c,7}$ (D=7)	$f'_{c,28}$ (D=28)	$f'_{c,3}$ (D=3)	$f'_{c,28}$ (D=28)
RMSE	2.22	1.44	2.14	1.26
MAE	2.00	1.00	2.00	1.00
EF (%)	93	96.9	88.5	96.7
Avg. Pi/Ai	1.09	1.01	0.89	0.98
Min Pi/Ai	1.02	0.95	0.75	0.93
Max Pi/Ai	1.24	1.08	0.95	1.02

different ages for the local aggregate concrete. Data used for the test purpose are named Group-4. Some ten results from total 27 tests are compared inTable VI. Finally, the overall prediction performance for local aggregate concrete is sumarrised in the Table VII.

VI. RESULTS AND DISCUSSIONS

A new model for prediction of compressive strength from an early day test result is presented. The proposed model makes use of the strength gaining characteristics of normal weight concrete as its base. Two groups of test data are used to develop the model while its performance is checked with four groups of test results. Concrete made with two different types aggregates viz. stone aggregate and local (brick chips) aggregates are included within the four groups considered. For analysis and model purpose stone aggregate concrete data are used (Group-1 & Group-2). Each data set, which corresponds to a particular concrete consists strength results at different ages. Performance evaluation is done with different data groups and the prediction is made for a particular day for which the test results are available.

TABLE VI. PREDICTED STRENGTH USING PROPOSED MODEL FOR LOCAL AGGREGATE CONCRETE DATA (GROUP-4)

Mix no.	Actual Strength, A_i ($f'_{c,D}$)				Predicted Strength, P_i ($f'_{c,D}$)		
					Using $f'_{c,7}$ value		
	$f'_{c,7}$	$f'_{c,14}$	$f'_{c,21}$	$f'_{c,28}$	$f'_{c,14}$	$f'_{c,21}$	$f'_{c,28}$
1	10.6	13.9	16.2	17.6	13.9	15.4	16.3
2	11.7	13.7	14.7	17.0	15.1	16.7	17.7
3	12.9	16.8	19.3	22.0	16.6	18.3	19.3
4	13.1	15.7	18.4	20.3	16.8	18.5	19.5
5	13.6	16.4	18.9	21.1	17.4	19.2	20.2
6	14.1	20.3	22.0	23.9	18.0	19.8	20.8
7	14.7	19.9	23.7	24.4	18.8	20.7	21.7
8	15.0	19.1	21.8	23.3	19.1	21.0	22.1
9	16.3	18.7	19.5	21.2	20.6	22.6	23.7
10	20.4	23.5	28.8	29.7	25.3	27.5	28.7

TABLE VII. PERFORMANCE SUMMARY FOR GROUP-4 DATA

Data	Group-4		
Used Strength ($f'_{c,D}$)	$f'_{c,7}$ (D=7)		
Predicted Strength ($f'_{c,D}$)	$f'_{c,14}$ (D=14)	$f'_{c,28}$ (D=28)	$f'_{c,28}$ (D=28)
RMSE	1.19	1.50	1.81
MAE	0.94	1.26	1.48
EF (%)	94.5	93.5	93.3
Avg. Pi/Ai	1.02	0.99	0.96
Min Pi/Ai	0.89	0.87	0.83
Max Pi/Ai	1.11	1.16	1.12

The performance measuring statistical parameters like Root Mean Square Error, Mean Average Error, percent Efficiency and ratio of prediction to actual values [RMSE, MAE, EF (%), and Pi/Ai] are used to check the efficiency of the proposed model for every group of data sets. Average values of these parameters are plotted in Fig. 2 and Fig. 3 for different groups. Fig. 2 shows that the RMSE value varies from 2.49 to 1.50 and the MAE ranges from 2.06 to 1.23. For both these parameters, minimum value occurs for local brick aggregate concrete. Fig. 3 shows variation of efficiency of prediction for different groups of data. It varies from 93.78 to 91.33% which is within a narrow band. From overall observation, it may be concluded that all the performance measuring parameters are within acceptable range.

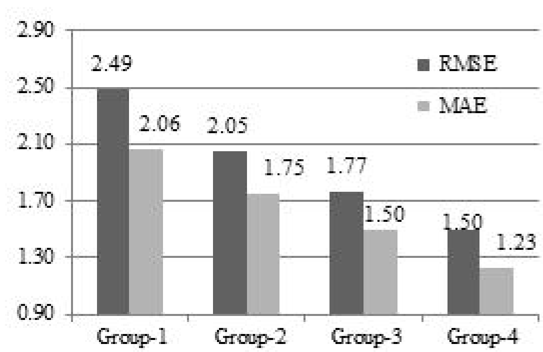

Figure 2.Variation of RMSE & MAE value for different groups

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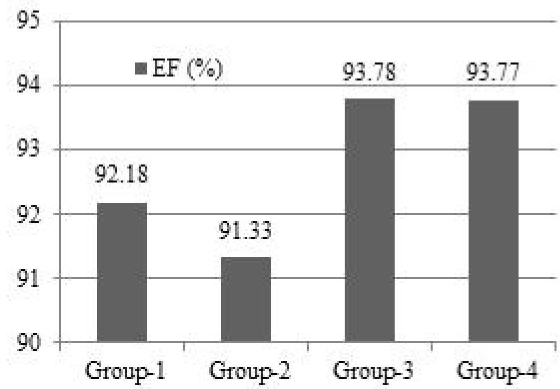

Figure 3.Variation of EF (%) value for different groups

VI. Conclusions

This study represents a simplified mathematical model for predicting concrete strength at different ages, just using any single day concrete strength test result. The proposed model shows the importance of two constants p and q, which regulate the concrete strength gaining characteristics with age. This study shows that, there is a relation (power equation) between the p value with the concrete strength of a particular day and the definite relationship with p value with strength at 3 days, 7 days and 14 days are established. Through this model the use of index properties of concrete [e.g. water, cement, water-cement ratio, FA, CA, density] are being eliminated. Validity of the model is established for both stone and local aggregate (brick aggregate) concrete. As the proposed model is verified with different data sources and shows a good efficiency to predict concrete strength, it may be used as a reliable tool for assessing the design strength of concrete from quite early age test results which can bring economy to the project and save both time and cost.

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